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Article

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Atmospheric electric fields

Karen Aplin and Giles Harrison examine international records of the 1859 Carrington flare and consider what they mean for our understanding of space weather today.

Space weather is increasingly recognized as a hazard to modern societies, and one way to assess the extent of its possible impact is through analysis of historic space weather events. One such event was the massive solar storm of late August and early September 1859. This is now widely known as the "Carrington flare" or "Carrington event" after the visual solar emissions on 1 September first reported by the Victorian astronomer Richard Carrington from his observatory in Redhill, Surrey (Carrington 1859). The related aurorae and subsequent effects on telegraph networks are well documented (e.g. Clark 2007, Boteler 2006), but use of modern techniques, such as analysis of nitrates produced by solar protons in ice cores to retrospectively assess the nature of the solar flare, has proved problematic (Wolff *et al.* 2012). This means that there is still very little quantitative information about the flare beyond magnetic observations (e.g. Viljanen *et al.* 2014).

Unexplored quantitative data

Solar energetic particle events affect the electrical properties of the atmosphere, some of which are detectable at the surface (e.g. Nicoll and Harrison 2014). Atmospheric electrical observations already established by 1859 therefore offer an alternative (and hitherto unexplored) source of quantitative data, analysed further here. In 1859, the fundamental parameter measured was the atmospheric electric field, which arises from the combined effect of global thunderstorms, creating a potential difference of about 250 kV between the conductive ionosphere and surface. Atmospheric electric field is conventionally measured as a vertical potential gradient (PG), which is positive and nominally $100\,\mathrm{V\,m^{-1}}$ in "fair weather" away from charge-generating processes such as active thunderstorms (e.g. Rycroft *et al.* 2012). The combination of charge separation in disturbed weather and current flow to fair-weather regions is known as the global electric circuit. The PG is sensitive to local effects, such as meteorological phenomena leading to rain or fog. Particulate air pollution, such as dust, reduces the air conductivity by removal of ions which ultimately increases the PG (e.g. Harrison 2006) and, conversely, ionizing radiation can enhance the local air conductivity and reduce the PG (e.g. Takeda *et al.* 2011). The atmospheric electrical measurements made in 1859 can therefore be expected to respond to both local and global meteorological and electrical conditions.

There are three possible routes through which a large solar storm might affect the PG. The first is by enhanced surface atmospheric ionization. Solar storms produce solar energetic particles (SEPs), some of which enter Earth's atmosphere – aurorae, for example, result from SEPs meeting the Earth's upper atmosphere. Some solar storms can produce particles that are sufficiently energetic (>1 GeV) to ionize the atmosphere down to the surface (Bazilevskaya *et al.* 2010). These events are known as ground level events or ground level enhancements (GLEs) and are expected to reduce the surface PG, because the ionization from particles reaching the surface would increase the air conductivity beneath the sensor.

A second type of atmospheric electrical response arises if the solar flare produces lower-energy particles that enter the atmosphere, but do not reach the surface. Under these circumstances, the global circuit would be modulated by decreasing the resistance of the air in the upper atmosphere, which would increase the conduction current between the ionosphere and the surface, in turn enhancing the PG.

The third, and least well-understood mechanism, would be through enhancement of lightning by SEPs (Scott *et al.* 2014), which would cause increased current flow in the global circuit and, if local variations did not dominate, yield PG fluctuations.

Although there is no quantitative evidence that the Carrington event produced SEPs, it is considered likely that it did, based on comparisons with other large solar flares (Cliver and Dietrich 2013). Any disturbances in the atmospheric electricity records therefore might provide new evidence for an SEP effect from the Carrington flare. Additionally, as only high-energy solar particles can reach the surface, understanding whether the Carrington event produced a GLE would help to constrain the energy spectrum of any particles from the flare.

19th-century data

Magnetic and atmospheric electricity measurements were often made together, but

during the Carrington flare

1 (Above): "View of Melbourne from the Observatory 1858" by George Rowe. The magnetic (conical white building on left-hand side, plus central brick building with domed roof) and meteorological (white stand with wind vane on top on right-hand side) measurement sites can be clearly seen (Hayes 2011). (Pictures Collection, State Library of Victoria)

2 (Left): Photograph of G B von Neumayer, who established the Flagstaff Observatory in Melbourne, taken by Frederick Frith in 1864. (Reproduced with permission from the Pictures Collection, State Library of Victoria)

atmospheric electricity has been neglected. Below, two little-known atmospheric electricity datasets, made at the magnetic observatories of Greenwich (London) and Flagstaff Observatory (Melbourne, Australia) are analysed. Although the Greenwich magnetograms during the Carrington flare are well known, the Melbourne magnetic data have been less well disseminated; we show digitizations below, to facilitate analysis of the atmospheric electrical data.

Magnetic and auroral effects of the Carrington event are so well documented in both modern (e.g. Clark 2007) and historical publications that only a brief summary is necessary here. A large ejection from the Sun was seen by Richard Carrington from his observatory at Redhill, Surrey, at 11:15 UT on 1 September 1859 (Carrington 1859). The "Carrington event" or the "Carrington flare" refers to the large solar emission on 1 September, with a smaller precursor on 28 August, that caused significant magnetic disturbances, including aurorae visible even in the tropics, and disruption to the telegraph network. Although details remain to be established, it is widely accepted to have been one of the largest solar flares in the era of quantitative observations. Those observations were provided by magnetic observatories, several of which were running by the mid-1850s.

By 1859, Greenwich Observatory in London had implemented photographic recording of its magnetometer data, and these measurements remain the only continuous record of the substantial disturbances associated with the flare, although the magnetograms have not been digitized (Greenwich 1859, Clarke 2014). Other observatories were making manual measurements of the magnetic disturbances associated with the flare, which, while less well sampled, do permit digitization. For example, the Helsinki data have already been analysed (Nevanlinna 2006), although data are missing because of the difficulty of sustaining manual observations during such variable conditions; additional data were provided by Russian stations (Nevanlinna and Häkkinnen 2010, Viljanen *et al.* 2014).

Flagstaff Observatory in Melbourne (figure 1) was established in 1858 by the German scientist Georg von Neumayer (figure 2) with joint Australian and German funding. The observatory was located on Flagstaff Hill, to the northwest of the city (37.810°S, 144.953°E) and began meteorological observations on 1 March and magnetic observations on 1 May 1858 (Neumayer 1860). The rapid growth of Melbourne, particularly the expanding tram network, meant that the observatory was ultimately forced to close in November 1863 to move to the new Melbourne Observatory site near the Botanic Gardens in search of magnetically quiet conditions. The Flagstaff Hill site became a park in 1862; Flagstaff Gardens is still popular today.

Disturbances in Melbourne

Melbourne observers first noticed magnetic disturbances soon after 7 p.m. local time on 28 August 1859. Between 8 and 9 a.m. on 29 August it was reported:

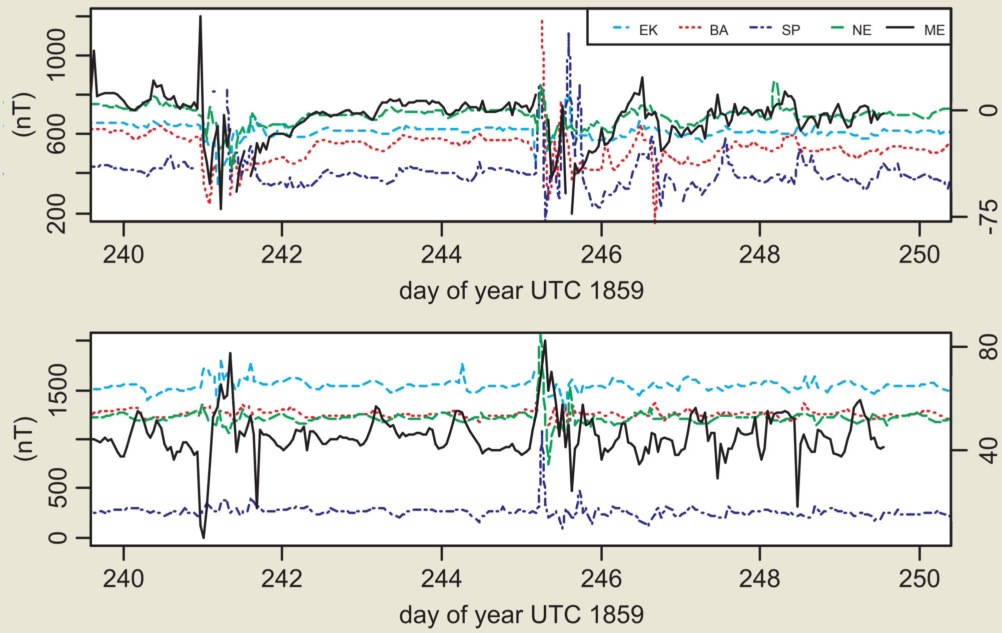
> *"[the] magnets were disturbed very violently… The disturbances continued with more or less intensity until 4 am on the 30th, the horizontal force and declination not having up to this time, returned to their normal values. It was an interesting fact that during the whole of the 29th, the instruments of the Electric Telegraph were disturbed to such a degree as to interfere with the working of the lines, extended over New South Wales, South Australia and Victoria".*

According to Boteler (2006) a "solar flare effect" is discernible as a fluctuation in the Greenwich magnetograms lasting about an hour at 11.15 a.m. local time, caused by solar

1: Atmospheric electrical observations at Greenwich during Carrington flare

date (yearday); notes on meteorological and magnetic conditions	midnight–noon	noon–6 p.m.	6 p.m.–midnight
28 Aug (240); first disturbance ~23:00	*strong*	*weak*	*weak*
29 Aug (241); first disturbance persists until 10:30	weak	zero	weak negative
30 Aug (242); 0.8 mm rain	weak	very strong negative and positive, with sparks	zero
31 Aug (243)	*zero*	*zero*	*strong*
1 Sep (244); flare seen from London a.m. (with a minor local magnetic disturbance); foggy p.m.	*medium*	medium	strong
2 Sep (245); maximum magnetic disturbance from approx. 05:00–14:30; 5 mm rain	weak	zero	zero
3 Sep (246); foggy/hazy	zero	zero	zero
4 Sep (247)	weak	*zero*	*zero*
5 Sep (248)	*zero*	*zero*	*zero*
6 Sep (249); 7 mm rain	strong	strong negative and positive, with sparks and galvanic currents	zero
7 Sep (250)	*weak*	*zero*	*weak*
8 Sep (251)	weak	zero	zero

Atmospheric electrical observations at Greenwich Observatory during the Carrington flare, with notes on the meteorological and magnetic conditions at the same site (Greenwich 1859). "Fair weather" periods were determined on the basis of the meteorological observations and are italicized.



3: Digitized magnetic observations: (top) horizontal force, (bottom) declination, during the Carrington event from Melbourne (ME) in Australia, and Ekaterinburg (EK), St Petersburg (SP), Barau (BA) and Nertchinsk (NE) in Russia. The Russian data are plotted in nanoTeslas on the left-hand axis, whereas the Melbourne data are uncalibrated and plotted on the right-hand axis. The Melbourne data are tabulated in Neumayer (1860) and the Russian data are described in Nevanlinna and Häkkinnen (2010) and Viljanen *et al.* (2014).

particles impacting the ionosphere, but the hourly samples of the Melbourne magnetic data make identification of the local flare arrival time difficult. On 2 September, "at about 3.30 p.m., the magnetic elements began to be disturbed", and "at this time, the declination, intensity and inclination instruments could not be registered, as the scales were out of the field of the telescopes". Disturbances continued until 6 a.m. on 3 September, and signals returned to normal about 3 p.m. that day (Neumayer 1859, 1860). Atmospheric electricity measurements were maintained at Melbourne during the storm, and will be discussed below.

To understand the atmospheric electrical effects of the Melbourne magnetic storm, the magnetic data are first verified by comparison with the Russian series mentioned above. To do this, the local time must be understood in terms of universal time (UT). As discussed by Humble (2006), this is not straightforward, but the best available estimate, used here, is that Melbourne was 9 hours 40 minutes ahead of Greenwich time. The Russian and Melbourne data are plotted in UT in figure 3 (time conventions for the Russian data are better established [Nevanlinna 2008]). The character and relative magnitude of the changes at Melbourne are consistent with those recorded at the Russian stations.

Atmospheric electricity observations

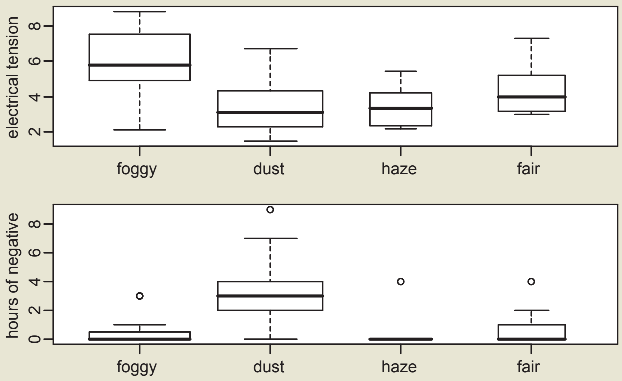
Qualitative observations of "electricity" from a flame probe were made at Greenwich Observatory during the Carrington event (Greenwich 1859). The flame probe potential equalizer, known as the "electric light" (Glaisher 1844),

2: Electric tension at Melbourne in spring 1859

weather type	median electric tension ±standard error at Melbourne, 5 July – 1 November 1859	typical potential gradient	reference
fair weather	3.96±0.24	+150–200V/m	Bennett and Harrison 2007
fog	5.75±0.43	+200–1000V/m	Bennett and Harrison 2007
dust	3.13±0.09	negative	Balme and Greely 2006
haze	3.35±0.2	positive, between fair weather and fog	Aplin 2012

Electric tension at Melbourne in spring 1859 under different meteorological conditions, and comparisons with modern data.

4: Electric tension measured at Flagstaff Observatory, 5 July to 1 November 1859, under different meteorological conditions. (Top): Positive electric tension. (Bottom): Number of negative excursions. In the boxplots the central line is the median, the upper and lower limits of the box represent the interquartile range, and the whiskers show the minimum and maximum values of tension. Outliers greater than 1.5× the interquartile range are plotted as points, in the lower panel.



was a standard technique at the time for measurement of atmospheric electric fields (e.g. Aplin and Harrison 2013). Ionization created by the probe makes the air conductive near the flame, which allows the probe to acquire the same potential as the air. The atmospheric potential is then measured using a sensitive high-impedance voltmeter and an electrometer. It is unclear what type of electrometer was used for the measurements during 1859, but in 1847 five different types of electrometer of different sensitivities seem to have been in use, indicating some experimental rigour. The electrometers were connected, through what might now be called a junction box, to a flame probe on the roof of the building (Airy 1847). The qualitative observations used a code to indicate the strength of the electricity measured from the flame, from "o" for zero, to "m" for moderate, "s" for strong, and "sps" for very strong, strong enough that sparks could be drawn from the electrometer. Sign was indicated by "P" and "N" for positive and negative. Measurements were taken at nominal 12-hour intervals, "AM" and "PM", with subdivisions whenever events of interest, or rapid changes, occurred. Quantitative observations of pressure, temperature, rainfall and cloud were also made at the same time, which permits identification of "fair" and "disturbed" weather in the atmospheric electrical data. The data are reproduced in table 1.

"Fair weather" periods were limited during the flare period, though the sky over London and the southeast of England was fortuitously clear for Carrington's famous observations on the morning of 1 September. There are some problems with the Greenwich atmospheric electrical data, such as the inconsistent response of the electrometers to consistent meteorological conditions. London was notoriously foggy and polluted during the 19th century, causing high atmospheric PG (which can also be used to retrospectively determine historical pollution levels (Harrison and Aplin 2002). At Greenwich, fog and strong electricity were recorded on the afternoon of 1 September, whereas 3 September was foggy or hazy all day, yet zero electricity was measured. These inconsistencies make it difficult to use the Greenwich data to look for any fair-weather effects of the Carrington flare. However, strong electrification was associated with wet weather on both 30 August and 6 September, when the magnetograms were slightly disturbed. Further analysis would be needed to determine whether strong electrification in the absence of thunderstorms was common or not at Greenwich, but if this data is indeed anomalous, it could provide evidence for solar storms enhancing atmospheric electricity in disturbed weather (Scott *et al.* 2014).

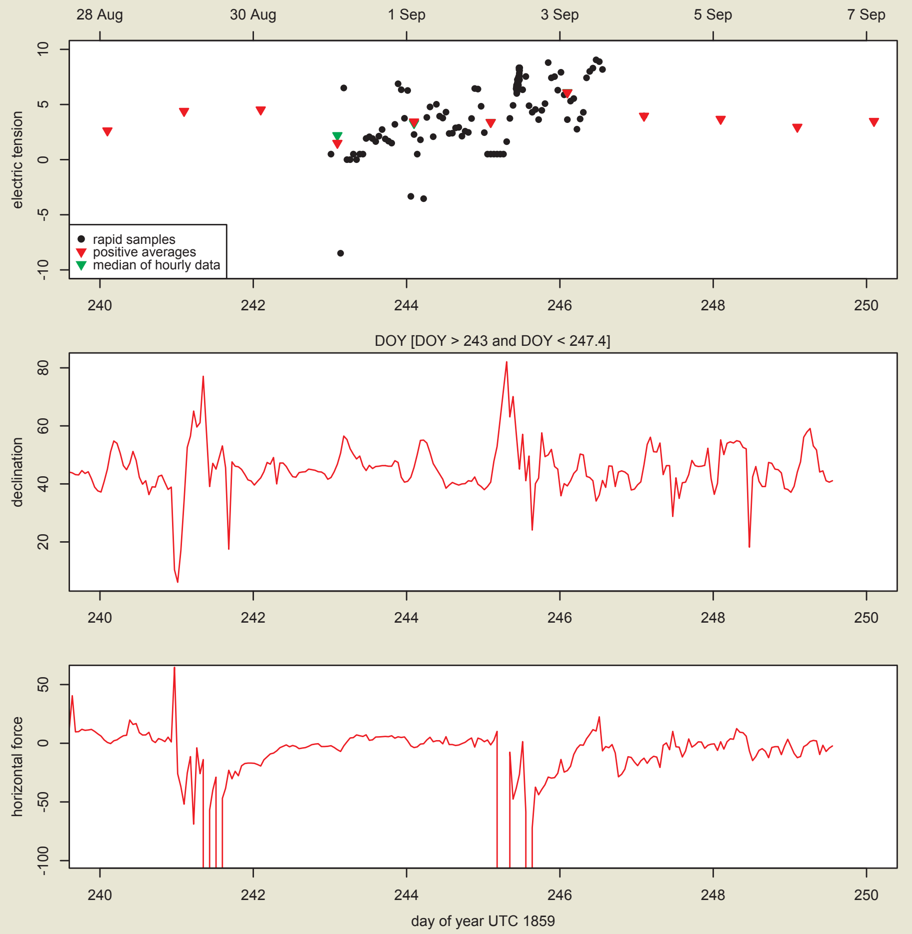
Flagstaff measurements

Atmospheric electrical measurements were considered to be meteorological observations, and were regularly made at Flagstaff from 15 April 1858 to 21 September 1862 (Neumayer 1860, 1867). As at Greenwich, the sensor was a flame probe located on the roof of a building, but unlike Greenwich, "burning fungus" was used to maintain the flame (Ellery 1876).

The measurements were usually made hourly by an observer physically connecting the top part of the electrometer to the sensor. The electrometer was then returned to its stand, which was mounted on a brick wall to minimize vibration, for the deflection to be measured. This exercise was repeated three times, separated by one minute each, and a final "electric tension" obtained (Neumayer 1860). It was not possible to determine an absolute calibration for the Melbourne electrometer readings until the 1860s (Ellery 1868), so "electric tension", which was simply the electrometer deflection in degrees and minutes, was recorded. On the basis of figure 2, which is known to be an accurate representation of the observatory buildings – and even some of its visitors (Hayes 2011) – the only possible brick wall is the structure with the domed roof at the centre, which must have had the flame probe on its roof. The "platform on the roof of the observatory" described by Neumayer (1860) would therefore be the flat white structure visible on the top of the dome in figure 2, although there is no evidence of any instrumentation on the outside of the building in the picture.

The quantity and quality of observations recorded at Flagstaff during its relatively short period of operation allow a good picture of typical variations in atmospheric electricity to be obtained. The logbooks (Neumayer 1860, 1867) record the daily mean values of positive electric tension with detailed meteorological measurements and a description of the weather, including aurorae, each day. Negative and zero values were not included in the average, but the number of negative and zero hourly registrations were tabulated alongside the means. The sign of electricity measured is consistent with modern understanding of the atmospheric electrical potential gradient (the negative electric field) which is positive in "fair weather" undisturbed by thunderstorms, and negative in disturbed weather such as during rain or storms.

To place the observations during the Carrington flare period in the context of the typical conditions expected at the station, the variations in tension at the same time of year as the flare have been digitized and sorted according to the daily observations (table 2) to permit comparisons with modern analysis of how PG varies with different weather conditions (Bennett and Harrison 2007). In fog, the PG is substantially enhanced because of the attachment of ions to droplets, whereas in a dust storm, the PG is usually negative. At Melbourne, the greatest median tension occurred in fog, and the least tension (together with the greatest number of negative readings (figure 4) are associated with the dust storms that were common at the site. Haze is typically associated with slightly enhanced PG, and while the haze tension is not significantly different to the fair weather tension, it is clear that there were few negative readings during both haze and fog. Fair weather gives rise to a moderate PG, between that of fog and haze, arising from the global atmospheric electric circuit (Bennett and Harrison 2007), with relatively few negative excursions. Demonstrating that the Melbourne atmospheric electricity data set is consistent with current understanding of atmospheric potential gradient readings gives confidence in the overall quality of the Flagstaff data.



5: Atmospheric electrical and magnetic changes at Flagstaff Observatory, Melbourne, during the Carrington flare period. 1 September was year day 244. (Top): Atmospheric electrical observations, with the daily average positive tension (Neumayer 1860) compared to both the rapidly sampled data (Neumayer 1859) and the derived daily medians. (Middle): The magnetic declination and (bottom) the horizontal force (with over range values during the storm maxima), which allows the local time of the storm maximum to be established (Neumayer 1867).

Anomalous behaviour

Observatory staff recognized the anomalous behaviour of their magnetic instruments during the Carrington flare. In a special article in local newspaper the *Melbourne Argus*, a detailed report of the weather and aurorae observations was presented, as well as the hourly observations of the electric tension made during the most magnetically disturbed period from 31 August to 3 September (Neumayer 1859), and every couple of minutes during a period from 7.59–9.05 p.m. when the aurora was at its most variable. (The date of the highest frequency readings is not stated, but is assumed to be 2 September, the day with strongest auroral activity. It is also unclear whether the readings took place in the morning or the evening, but the aurorae would only have been visible after sunset.) The conclusion drawn at the time was that, "the electric tension of the atmosphere appears not to have been greatly disturbed", although, interestingly, "the effect [on the telegraph] was similar to that produced by atmospheric electricity", implying that magnetic and atmospheric electrical disturbances may have been correlated previously (Neumayer 1860).

The electrical tension may show some enhanced variability during the maximum flare period, as defined by the local magnetic changes (figure 5). In particular, there were "vivid sparks, with a loud noise" from the electrometer on 31 August, indicated on the top panel of figure 5 as strong variability and negative excursions. There was also variability on 1 September and an increase in tension from 2–3 September. In terms of the local weather conditions, there was a dust storm and squally rain on 31 August, both of which could easily have caused the strongly enhanced negative tension observed at Melbourne that day. The days 1–4 September were, however, reported to be fair, as a high-pressure system moved in (Neumayer 1859).

Geomagnetically induced currents, i.e. directly induced currents in the instruments and cables used, are not thought to have been responsible for any of the changes seen, because they would be expected to cause synchronous effects in both the electrometer and magnetometers. No such effects are seen in figure 5, though there may be some similarity between the electrical tension, slightly lagging changes in magnetic declination, on 2 September.

The daily mean tensions from 1–4 September were consistent with expectations based on the meteorological reports, with one exception. The positive average on 3 September was greater than usual, at 6.08, whereas the typical tension expected in fair weather is around 4 (figure 4). The tension on 3 September is in the upper decile of all tension readings for spring 1859. Out of the nine readings in the upper decile of tension measurements, six of them were in foggy conditions; this extreme value is relatively unusual for fair weather. In particular, the meteorological reports for 3 and 4 September are almost identical, but the tension was 50% higher on the 3rd. Although the solar storm was at a maximum at Flagstaff on 2 September, the tension enhancement on the 3 September remains unexplained.

Discussion

Two little-known sets of atmospheric electricity measurements made at magnetic observatories strongly affected during the Carrington event have been presented. Qualitative observations from Greenwich Observatory are probably not sensitive or consistent enough to detect any "fair weather" effects of the Carrington event. There may have been some effects of SEPs in disturbed weather, but statistical analysis of the Greenwich data would be needed to understand whether the strong electrification during showers seen during the Carrington event was truly anomalous.

Flagstaff Observatory at Melbourne offers a high-quality set of PG data which, although uncalibrated, behaves consistently with modern

3: Known atmospheric electricity data, 1840–1860

start date	end date	quantity measured	location and name of principal observer	data source
1842	1844	"electricity"	Brussels Observatory, by Quetelet	McAdie 1897
1843	1847	"electricity" (with magnetic and meteorological measurements)	Kew Observatory, by Ronalds	e.g. Scrase 1934, Hackmann 1994
1847	1926?	"electricity" (with magnetic and meteorological measurements)	Greenwich Observatory, initially by Airy	logbooks available online from British Geological Survey http://www.bgs.ac.uk
1850	1851	"electricity"	Munich Observatory, made by Lamont	McAdie 1897
1850	1851	"electricity"	Kreuznach, Germany, made by Dellmann	McAdie 1897
1858	1863	"electric tension" (with magnetic and meteorological measurements)	Flagstaff Observatory, Melbourne, set up by Neumayer	Neumayer 1860, 1867; Ellery 1876
1859	1861	"atmospheric electricity"	various Scottish sites (Arran, Aberdeen, Glasgow), made by Lord Kelvin	see Aplin and Harrison 2013
1852	1866	"atmospheric electricity"	balloon measurements by Welsh, Glaisher and Coxwell	e.g. Hunt 1996 and references therein

understanding of PG responses to weather. Similarly reliable magnetic observations offer a way to identify the local storm maximum at Melbourne. Analysis of the PG and weather during the Carrington event indicate that there was unusually high PG on 3 September, which is not easily explained in the absence of fog. This is unlikely to have been caused by a geomagnetically induced current in the instruments, as there were no synchronous variations in the magnetic and electrical instruments at any point, even during the storm maximum. If the PG enhancement on 3 September was associated with the Carrington flare, the data do not support the idea of a GLE at Melbourne, as there was no increase in surface conductivity. The increase in PG implies that, at least for the second phase of the storm, the energy spectrum of the solar particles was softer, with the particles only reaching the upper atmosphere to decrease the resistance there, and increase the surface PG.

In conclusion, historical measurements of atmospheric electricity offer an under-exploited source of data for understanding past meteorological and solar–terrestrial events. Some serendipity may be needed in both finding and analysing the data. For example, it is curious that a sudden, temporary failure of atmospheric electricity apparatus used by Lord Kelvin coincided with the Carrington event (Aplin and Harrison 2013), which provides an intriguing postscript to Kelvin's long-held view of the Sun having no magnetic influence on the Earth (Thomson 1892). For further investigations it is of central importance to establish what other atmospheric electricity data sources may be available, and those known to have been made during the 1850s are summarized in table 3. Further insights into these or other sources are most welcome. ●

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